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Power generation using district heat: Energy efficient retrofitted plus-energy school Rostock

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Abstract

The Mathias-Thesen-School in Rostock / Germany is one of few schools which has been retrofitted as an Energy Plus building as part of the energy-efficient school research project "EnEff:Schule" sponsored by the German Ministry of Economics and Technology. The original building complex (build 1960, useful area 2200sqm) is being converted into a compact building by extending the main building with two new buildings connected by light-flooded buffer spaces. Both the existing building and the new buildings will be highly insulated. The low remaining heating demand will be covered using an innovative concept, made reasonable by the low primary energy factor of the district heat in Rostock: A small-scale Organic Rankine Cycle system generates electricity using high-temperature district heat. The excess heat of the generator is then used to heat the building via low-temperature distribution systems. In combination with two small-scale onsite wind turbines and building integrated photovoltaics a positive primary energy balance is achieved. For this balance, the development of the primary energy factors (PEF) of the German electricity mix is crucial: With rising generation from renewable energies the PEF of electricity in Germany is going to descent, leading to higher primary energy factors of cogeneration systems. In the Mathias-Thesen-School in Rostock a detailed monitoring system was installed, which has been checked and reworked for proper functioning. First measures to optimize the HVAC system and user comfort have been taken. The second construction phase will take place in 2014, after which the performance of the ORC system and the Energy Balance will be analyzed in detail.

Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG

Keywords: Retrofit; Plus Energy; School; Comissioning; Disctrict Heat; Primary Energy; Comfort; ORC; Organic Rankine Cycle; Germany

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1. Introduction

Knowing that energetic retrofitting is an urgent need, the German Ministry of Economics and Technology (BMWi) sponsors the retrofitting of buildings in the project “EnOB: Research for energy-optimised construction”. Its aim is to gather and display the results of the scientific evaluation of the buildings performance, thus monitoring is a must. A subproject of EnOB is EnEff:Schule, under which demonstrator projects of newly constructed and retrofitted schools are subsumed. The Mathias-Thesen-School is one of the most ambitious of those demonstrator projects, as it is laid out to be a Plus-Energy School, aiming for a positive annual primary energy balance.

Simultaneously with retrofitting innovative processes and components were installed and are to be tested in subsequent operation in terms of energy.

The purpose of the accompanied research project is therefore:

- to investigate the functionality of the new technical components, construction methods and building details used in the retrofitting,
- to prove the energetic balance of the building on the basis of actual energy flows and to demonstrate the feasibility of the energy concept [1,2],
- to test new methods of heating control (dynamic setback, integration of simulations with predictions) [3],
- to enable a vibrant knowledge in schools about physical and technical variables and technical procedures in relation to the theme of "Energy in Buildings"

The key objectives of the project are:

- to provide evidence of a positive primary energy balance,
- to gain experience in new building components,
- to verify the approaches and underlying assumptions of the calculation procedure of the German building energy code DIN V 18 599 [4,5],
- to make the major findings accessible to a broad audience as well as to potential multipliers (e.g. architects),
- to directly demonstrate and illustrate the possibilities of energy saving potentials to the users (teachers and students).

Fig. 1. Pictures of the building after finishing the first construction stage.

Retrofitting of the school started in 2011, with first plans dating back to 2008. In the first construction phase, the primary school part and the buffer zone were erected. It was finished in October 2012, the primary school part is in operation since then. The work for the second construction phase will start in November 2013 and are expected to be finished at the end of 2014. As the PV and ORC systems will be installed during the 2nd construction phase, the results of the energy balancing are not yet available. This paper focuses on the HVAC System operation and the room comfort during the summer period 2013.

2. Retrofitting concept

2.1. Building retrofitting

The Mathias-Thesen-School in Rostock-Reutershagen / Germany was built in 1960/61, had three connected buildings (Fig. 2 left) with a net floor area of 2200 sqm and an Area to Volume Ratio (A/V) of 0.38. Nearby there was a second identical school building, which isn't used anymore, both schools are now together in one compact building. This type of school was similarly built in several places in the Eastern part of Germany. The retrofitted building (Fig. 1 right) has a useful area of 5200 sqm with an A/V ratio of 0.21 and a highly insulated building envelope. Unconditioned buffer zones (transparent parts in Fig. 2 right) connect the individual building parts. The new school combines elementary school and grammar school and is intended for highly talented pupils. The architectural concept follows its guideline to show the technical systems installed in the building so the pupils can experience and understand the functioning of the building.

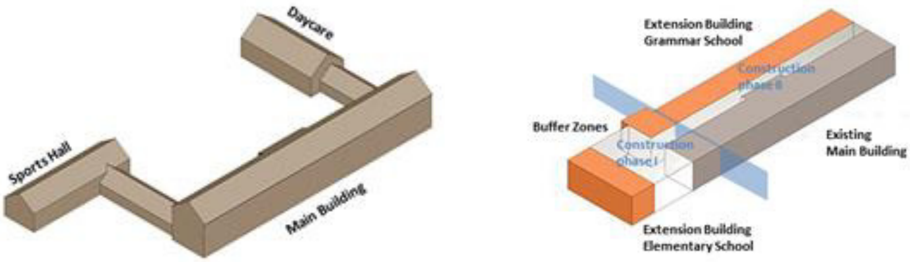

Fig. 2. Model of the building complex before (left) and after retrofitting. The buildings Sports hall and Daycare are demolished due to bad state of construction. Source: IGEL

The retrofitted school is equipped with a mechanical ventilation unit with heat recovery, located at the top floor of the building. Heat is distributed using a hybrid system of supply air heat exchangers, radiant ceiling panels, baseboard heaters and radiators. The first construction stage was finished in October 2012.

The calculated heat demand of the Mathias-Thesen-school in Rostock is (in accordance with DIN 18599 [4]) at 324.4 MWh / year or 51.3 kWh / (m² a) for heating and hot water, including distribution losses. The final energy demand for lighting, ventilation and power supply is (in accordance with DIN 18599) 122 MWh/a or 19.2 kWh / (m²a). However, measurements data of several schools in Tübingen show a significant scatter of the specific power demands [6]. Also the demand calculations of the school discussed here show that the uncertainties of the assumptions of school kitchen areas, computer science rooms and ventilation system have great influence on the total electricity consumption. Thus, it is crucial to add a safety margin to the installed electricity generation capacities in order to achieve a surplus in the energy balance.

2.2. Available resources for a Net Zero Energy building concept

With the Mathias-Thesen-school in Rostock the Energy balance is defined as a net balance based on the non-renewable part of the primary energy (PE) on an annual base. The ratio between end energy and the non-renewable part of primary energy ("PE-factor") depends on the actual share of renewables in the mix of sources in the electrical grid, which changes over the years and therefore is not a time invariant metric. PE-factors for the renewable energies photovoltaic and wind are constant for themselves, but changes in the German electricity mix with increasing share of renewables will lead to a higher share of renewable energies, and thus the PE factor for the electricity mix will continuously fall. This affects heating systems connected to the electrical grid: district heating based on cogeneration, local co-generation as well as heat pump systems. The following example assumes that the primary energy factor of currently 2.6 is changing to 2.0 due to a higher share of renewable energy. It is shown in Fig. 3: When using a cogeneration plant with an electrical efficiency of 35%, the primary energy factor for the heat increases from 0.24 at an electricity-mix-PE of 2.7 to 0.62 at an electricity-mix-PE of 2. Locally produced electricity fed-in is valued as charged electricity from the grid.

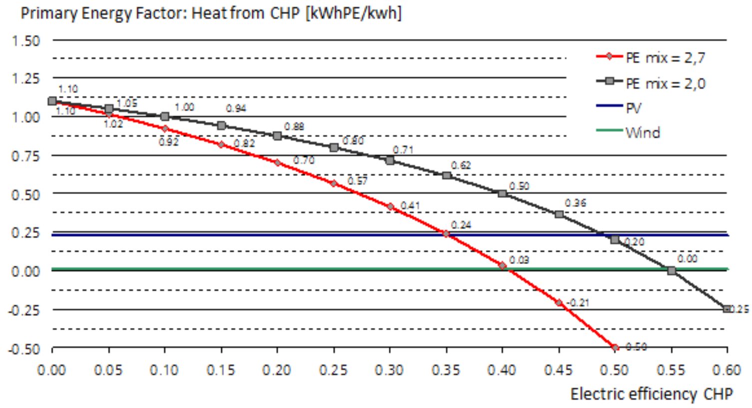

Fig. 3. Change of primary energy factors of a CHP based on the electrical efficiency when the proportion of renewable energy in the electricity mix of Germany is increased and the PE factor for this mix is reduced from 2.7 to 2.0

2.3. Plus energy concept: Power generation from PV, wind and ORC

The Energy supply concept for the school reflects these developments. District heat was chosen as heat supply because of the very low primary energy factor of 0.08 in Rostock. With the primary energy factor of 0.08 of the district heat of Rostock in 2012, the heating energy demand of the school equals 4.1 kWh / (m² a) primary energy. Therefore the heat energy supply is done by district heating. The on-site electricity generation is composed out of a building integrated PV system, two wind turbines and a ORC plant (for demonstration only). For the first time the district heat with a temperature level of 80-100 °C is used to generate electricity using a ORC system (nominal power 4 kW) before the heat is supplied to the building. The ORC system can be operated in two different hydraulic configurations, leading to a significant increase of the number of full load hours. The two wind turbines with a rated power of 3.5 kW are integrated in the construction of the external staircases. The innovative photovoltaic system to be integrated into the building envelope and consists of a combination of highly efficient modules with over 20% efficiency and translucent PV with 14.5% efficiency. The translucent glass-glass modules in the ceiling of the hallway and on the facade the photovoltaics are visible both from inside and outside. Furthermore the translucent modules at the hallway provide further improved daylight usage, and, as those on the facade are consoles over the windows, they function as a seasonal sun protection, too. With a nominal power of 145 kW and an annual yield of 130 MWh the PV system also ensures that the primary energy balance of consumption and local production (with respect to the values of the EnEV 2012) is expected to be positive.

Fig. 4. On-site installed wind generator (left); distribution systems installed in classrooms: baseboard radiators at the floor, ceiling radiator panels and yellow inlet air duct above the whiteboard (center); Window façade of the classrooms (right).

While in many low-energy buildings heating via the air is sufficient, school buildings need distribution systems, which can react quickly and which are able to distribute high peak heating loads: In the early morning, the empty classrooms have to be heated to 20 °C before the pupils arrive. During the lessons, the high density of persons leads to high internal gains, which could lead to an overheating when using high capacity distribution system such as Concrete Core Conditioning. During the day, full occupation and no occupation can vary from hour to hour, leading to steep changes in the necessary heating power of that individual room. Therefore, in the Mathias-Thesen-school a combination of several flexible distribution systems is used in the classrooms: Baseboard radiators supply basic heat and ceiling radiator panels are used to quickly heat up the room, Furthermore air heat registers avert too cold supply air. Each room has an individual controlling unit, which is able to control baseboard heaters, ceiling radiator panels and ventilation rate in dependence of room temperature, presence, air quality and window status. This ambitious concept was chosen to achieve a maximum of energy savings regarding the ventilation unit, but also to minimize the heating demand. As stated above, district heat was chosen as heat supply because of the very low primary energy factor.

3. Monitoring

The school building is equipped with an extensive monitoring system. Its data will be used for detailed energetic analysis and to prove the primary plus energy balance. The planned optimization and testing of different control strategies relies on detailed measurements in the HVAC system. Furthermore, the comfort conditions in combination with the user behavior will be analyzed, and the monitoring system is an important key during commissioning, to ensure that all systems indeed work as intended.

In each room, temperature, CO_2-concentration, presence, window status and air flow are monitored. Selected rooms are equipped with additional sensors for brightness, humidity and wall surface temperatures. In those reference rooms, separate heat meters are installed for both room distribution circuits (baseboard radiators and ceiling radiator panels), and lamps and power outlets are measured separately. Additionally, short-term comfort measurements are performed with mobile high-quality equipment (see Fig. 6). Thus, room comfort and its interaction with the user behavior can be analyzed in detail. (e.g.: Above which room temperature does the user open the window? And how does the opening of the window affect the air quality?)

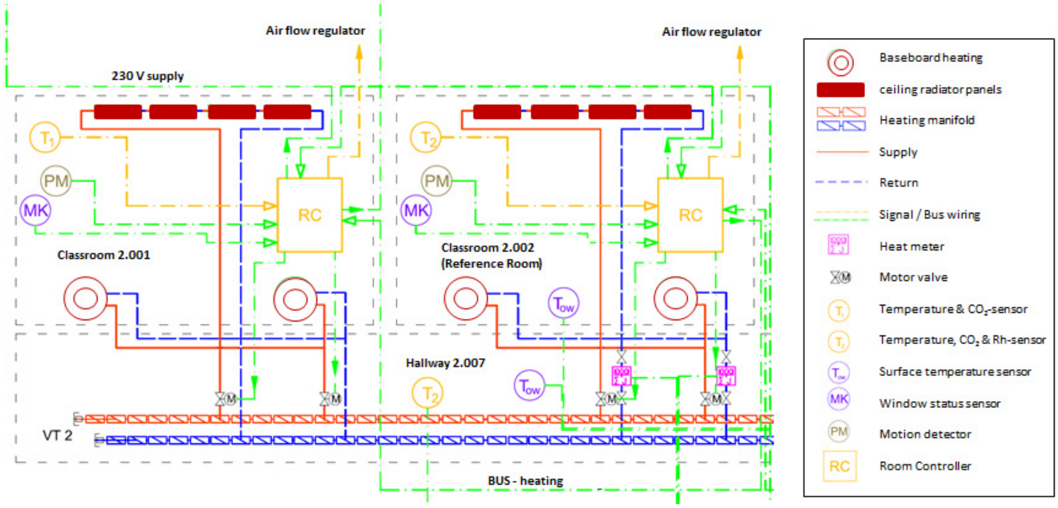

Fig. 5. Control and Monitoring System of a typical classroom (left) and of a reference classroom (right). Source: K&S

Electricity demand and generation are recorded with several energy meters. One meters the total consumption and generation, and several sub-meters are installed for the different generation systems and for the individual building zones. Counter values and current power values are both recorded to allow for accurate long term energy balances as well as for precise intraday-analysis. Pump energies, powers and heads are monitored by polling the pumps' bus modules. Heat meters are installed at the district heat connection, before and after the ORC-system, at each distribution system and, as said before, in selected reference rooms. Of each heat meter supply and return temperature, volume flow, counter value and current power are logged. Regarding the ventilation systems, temperatures before and after the heat recovery, heat supplied and pressure differences are measured as well as the air flow rates going to each individual room (the latter are calculated using the signals of the air flow controllers installed in each room). With all this data available, detailed analyzing, failure checking and optimization of the HVAC System are possible.

Fig. 6. Additional short term comfort measurements performed in the classrooms. The whole equipment is designed so that it can be moved to another classroom during one school break.

All data is collected via the building management system and stored as Event Data (meaning that the data is not stored in a fixed time step, but a new value is only stored if a sensor reading has changed more than a certain threshold. This threshold value is typically called "change of value" or COV). Once a day, all measurement data is copied to an ftp-Server, from where it is automatically downloaded and processed by the project partners. Furthermore, the data is accessible for evaluations done by the pupils, and main measurement data will be displayed on monitors in the hall way.

4. First project results

For a preliminary analysis monitoring data are available from May 10th till September 15th 2013 for the first construction phase, the primary school.

4.1. Commissioning of monitoring system

In the process of quality assurance for the monitoring system, all sensor readings were directly checked for functioning and plausibility by the monitoring team. This was done by visualizing the data using time series-, scatter- and carpet-plots and by cross-checking the sensors the sensors against each other (e.g.: The energy sum of all sub meters must not be higher than the total counter; If the window is opened or closed, user presence should have been detected in that room). A typical trouble which makes temperature readings unsuitable for highly detailed analysis is when the change of value of a temperature sensor remains at the default value of 0.5 K. Furthermore the permanently installed sensors were compared to the highest-quality sensors of the mobile measurement station for calibration purposes. All discrepancies were noted in a report by the monitoring team which then was processed by the building management system distributor. After two iterations, the accumulated data now is reliable and can be used for various further analyses. But also the data accumulated during the commissioning phase can already be used to analyze room comfort and the functioning of the HVAC system.

4.2. Comfort and building functioning

Fig. 7 shows the course of the room temperatures measured in the classrooms of the primary school in summer 2013. Before summer holidays, classroom air temperatures were between 23 and 29 °C. During the hot spell of July 2013, room temperatures reached a maximum of 26 to 32 °C. In this period, the classrooms were unoccupied because of summer holidays and thus the windows remained closed. The temperatures after mid of August were moderate.

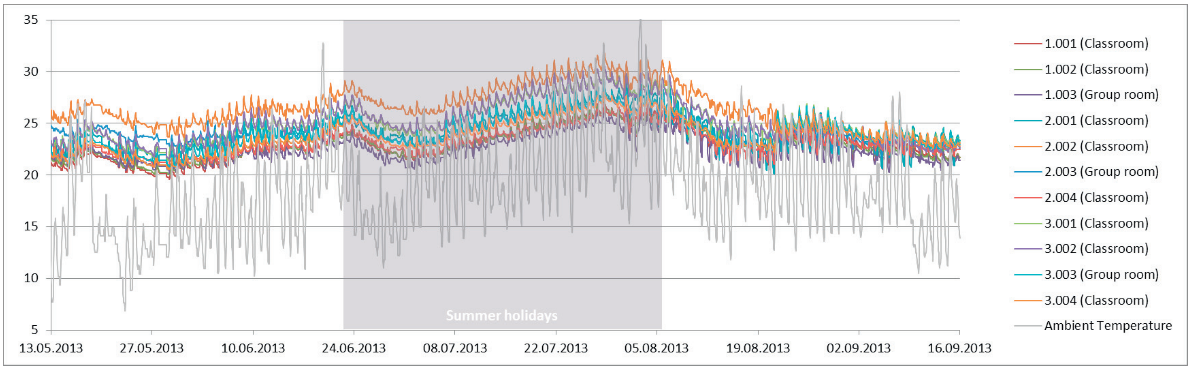

Fig. 7. Hourly Room Temperatures of all classrooms of construction phase 1 (primary school). The cool down effect of the night-cooling implemented on August 1st is clearly visible.

The room temperatures in the starting period May and June lead to various user complaints. All classrooms of the first construction phase are facing west with no shading devices installed, leading to high solar gains in the afternoon. Furthermore, the night ventilation concept was in-effective as the supply air was heated up constantly to at least 17 °C (either via the heat recovery or the air heat register, see Fig. 8), which prevented a cool down of the

rooms in the cold nights of the first half of June 2013. The set-point of 17°C for supply air could be found in various other buildings in order to prevent undercooling in summer and uncomfortable supply temperatures in winter. The measured results show, that such an implementation has to be adapted in highly insulated buildings.
In addition the windows could only be opened for a gap, due to storm protections (see Fig. 4). Furthermore, the school was still heated till July 15th. The combination of those factors lead to a heating up of the classrooms and were - respective will be - corrected. The room temperatures in the second half of the summer are promising.

For further analysis, the measurement data of an average performing classroom is shown: Fig. 9 displays temperatures, air quality, window openings and mechanical ventilation air flow of Room 2.001. The patterns visible there are similar for all classrooms: Before summer holidays, the ventilation system was operating with a nearly constant air flow from 1:00 to 23:00 on weekdays, without any dependence on CO_2-concentration or window openings. The CO_2-concentration exceeded 1500 ppm frequently, even when the windows were constantly opened during presence (June 10th till 21st). This was due to the mentioned storm protections, which allowed an opening of only about 10cm of the windows.

The process of rework started during the summer holidays 2013. The heating system was shut down completely till mid-September, the settings of the ventilation unit were changed starting at July 11th and the concept for night ventilation was revised and re-implemented at August 1st: In cold summer nights, the ventilation unit is operating from 0:00 till 6:00 with an air change rate of 2 h^{-1} and the heat recovery is bypassed. Furthermore, the teachers were instructed how they can open the windows up to 90° (longer storm protections are to be installed). These measures lead to a significant decrease of the room air temperatures and of the CO_2 levels, visible in both Fig 7 and 9.

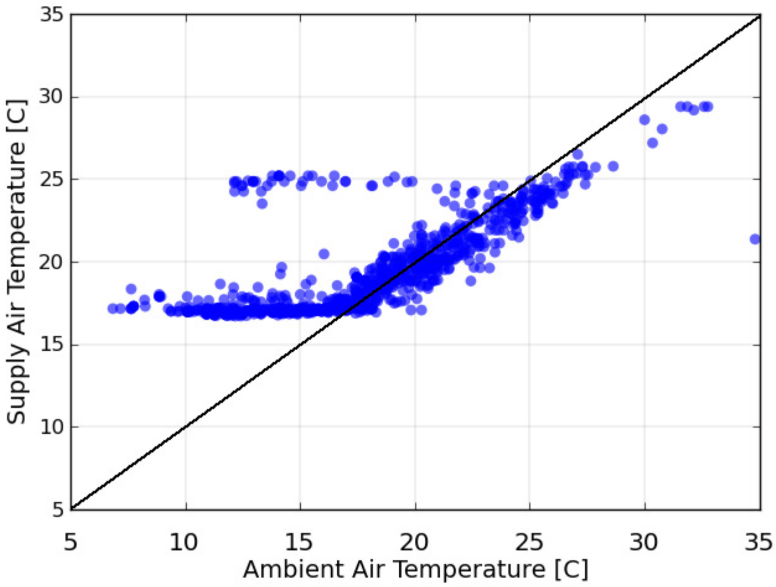

Fig. 8. Supply Air Temperature of the ventilation unit of the primary school part over the ambient temperature. Time range: May 10th till July 11th 2013 (begin of data till start of reworks). Displayed are hourly mean values, with the condition that the ventilation unit was operating with more than 20% of its nominal fan power at that hour.

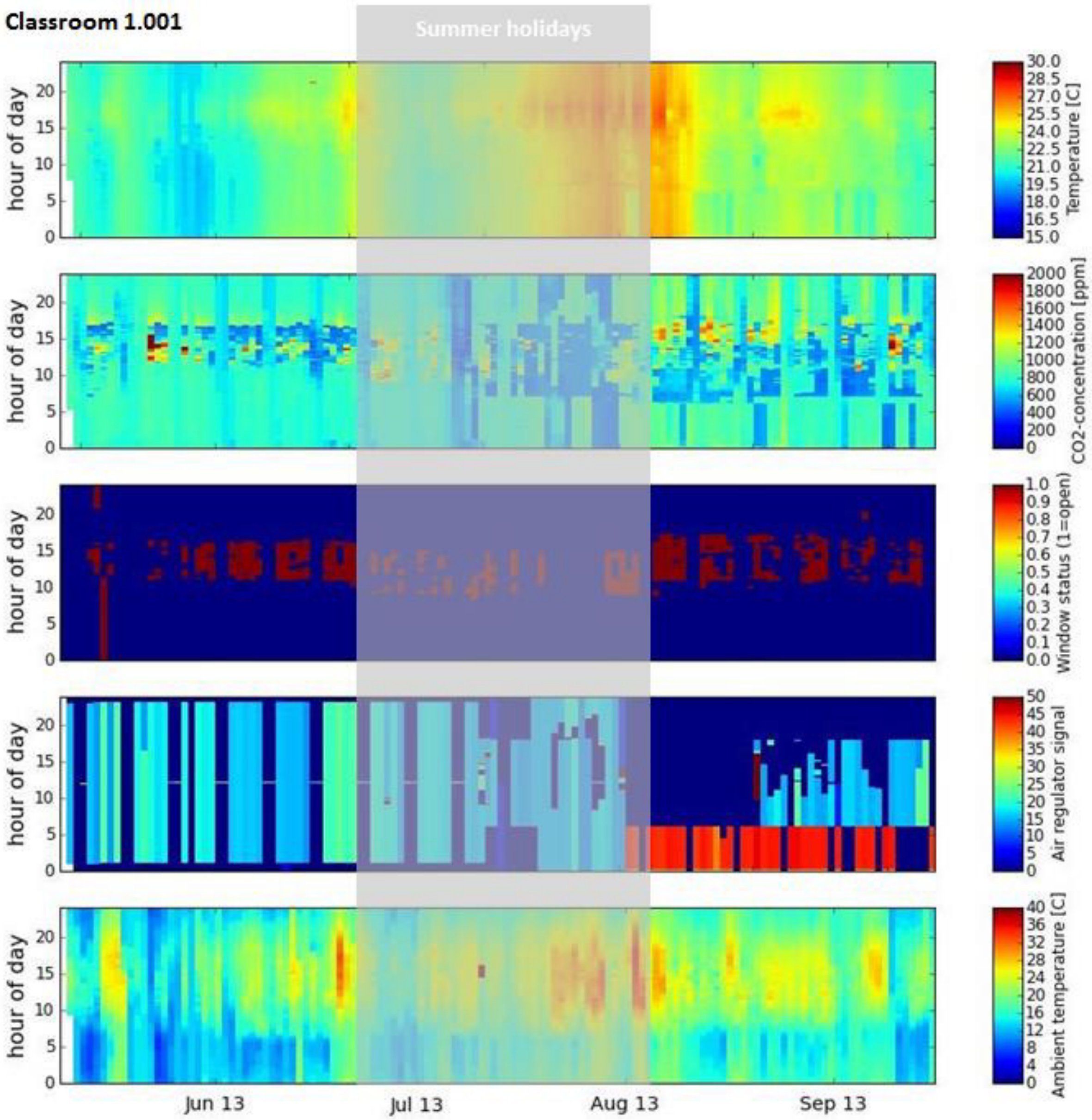

Fig. 9. Carpet-Plot of the average performing classroom number 2.001. Displayed are air temperature, air quality, window openings, mechanical ventilation and ambient temperature. The patterns visible here are nearly identical for all classrooms

5. Conclusion and outlook

The Mathias-Thesen-School in Rostock-Reutershagen shows that typical school buildings found in eastern Germany can be retrofitted to state-of-the-Art school buildings aiming for a positive primary energy balance. However, if the Plus Energy concept relies on cogeneration (either locally or by obtaining district heat from a cogeneration power plant), it is important to realize that the primary energy factor of this heat will increase with the rising share of renewable power generation in the national grid. This has to be reflected in the installed on-site renewable energy production when heading for an on-site annual net zero energy balance.

Especially when realizing ambitious HVAC systems, a detailed monitoring and commissioning is crucial to ensure that all systems work as intended. But also the monitoring system itself needs to be checked for proper functioning and recording of all sensors. If these prerequisites are given, a detailed scientific evaluation and an optimization of the systems can follow, leading to minimum energy consumption at a high user comfort level.

Effective measures to reduce an overheating of the classrooms of the first construction stage during the summer period were found by adapting the implemented night cooling and by allowing a wider opening of the windows. After the second (and last) construction phase of will be finished in 2014/15, its measurement data will show how well an ORC plant connected to district heat can perform and if the Plus Energy goal has actually been reached.

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